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Variability and Predictability of Land-Atmosphere Interactions: Observational and Modeling Studies

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Final Report 6/1/98-4/30/02
NASA GRANT NAG81516

The overall goal of this project is to increase our understanding of seasonal to interannual variability and predictability of atmosphere-land interactions.

The project objectives are to:

1. Document the low frequency variability in land surface features and associated water and energy cycles from general circulation models (GCMs), observations and reanalysis products.

2. Determine what relatively wet and dry years have in common on a region-by-region basis and then examine the physical mechanisms that may account for a significant portion of the variability.

3. Develop GCM experiments to examine the hypothesis that better knowledge of the land surface enhances long range predictability.

This investigation is aimed at evaluating and predicting seasonal to interannual variability for selected regions emphasizing the role of land-atmosphere interactions. Of particular interest are the relationships between large, regional and local scales and how they interact to account for seasonal and interannual variability, including extreme events such as droughts and floods. North and South America, including the GEWEX GCIP, MacKenzie, and LBA basins, are currently being emphasized. We plan to ultimately generalize and synthesize to other land regions across the globe, especially those pertinent to other GEWEX projects. The overall goal of this project is to increase our understanding of seasonal to interannual variability and predictability of atmosphere-land interactions.

1. Soil moisture composites

We completed construction of wet and dry seasonal composites have been constructed the mid-latitude GCIP region of the central US using long climate model simulations made with the NCAR CCM3 and reanalysis products from NCEP and NASA/DAO (Oglesby et al. 1998; 1999a,b) and published a major paper (Oglesby et al. 2001a) which has been accepted for publication pending revisions. Key results include: 1. Years that have increased MJJ soil moisture over the GCIP region also have high precipitation, lower surface temperature, decreased Bowen ratio, and reduced 500 hPa geopotential height (essentially reduced MJJ ridging). The reverse is true for years that have reduced MJJ soil moisture. Wet years are also accompanied by a general increase in moisture transport from the Gulf of Mexico into the central U.S. 2. There is some indication (though weaker) that soil moisture may then affect precipitation and other quantities and be affected in turn by 500 hPa geopotential heights. The correlations are somewhat low, however, demonstrating the difficulty in providing definitive physical links between the remote and local effects. 3. Analysis of two individual years with an extreme wet event (1993) and an extreme dry event (1988) yields the same general relationships as with the wet and dry composites. The composites from this study are currently serving as the basis for a series of experiments aimed at determining the predictability of the land surface and remote SST on the Mississippi River basin and other large-scale river basins. This analysis has now also been extended to two additional regions, the high-latitude Mackenzie Basin in northern Canada, and the low-latitude LBA region of Brazil, with results presented by Oglesby et al. (1999b).

2. Predictability Experiments

We have completed a first series of predictability experiments (Oglesby et al 2000b) in which we imposed soil water initial conditions in CCM3 for the GCIP region for June 1 from anomalously wet and dry years with atmospheric initial conditions taken from June 1 of a year with 'near-normal' soil water; and vice versa (initial soil water from the near-normal year and atmospheric initial conditions from the wet and dry years). A preliminary analysis of these results was presented by Oglesby et al. (2000b) and indicates that the initial state of the atmosphere is more important than the initial state of soil water in determining the subsequent late spring and summer evolution of soil water over the GCIP region. In a complementary study, we compared the impact of the initial condition of snow cover versus the initial atmospheric state over the western US (corresponding to the westward extension of the GAPP program follow-on to GCIP). Preliminary results were presented by Marshall et al. (1999; 2001) and suggest that in this case, the initial prescription of snow cover is far more important than the initial atmospheric state in determining the subsequent evolution of snow cover. We are currently working to understand the very different soil water and snow cover results.

3. Hydrologic Responses to CO_2

A number of climatological simulations and sensitivity experiments with the latest NCAR community climate model coupled to a sea-ice mixed layer ocean model (Roads et al. 1998b,c,d) were compared to NCEP reanalysis and each other. In addition to a control run forced by observed sea surface temperatures for the period 1950-1994, there have been a number of 20 year CO_2 simulations developed, ranging from concentrations of 100 ppm to 3000 ppm (Kothavala et al. 1999). Because of the potential intensification of the hydrologic cycle as the earth warms from increasing anthropogenic greenhouse gases, global cycling rates have attracted recent interest. It has been suggested that this cycling rate may be increasing, at least during the limited sample period. Roads et al. (1998a) suggested, however, that the cycling rate could ultimately decrease in the future, because the water vapor storage may increase relative to the precipitation rate. This decrease was confirmed in long period simulations and CO_2 simulations with NCAR CCM3.

4. Interannual Variability of CCM3 Tropical Precipitation

Many of our research results to date point to a substantial role for remote SST influences in affecting hydrologic anomalies over continental regions. This is particularly true for drought initiation and extreme events such as mid-latitude floods that have their origins in storm track anomalies. With this in mind we have begun to analyze tropical precipitation anomalies in a CCM3 integration forced with observed SSTs since 1948. In particular we have examined the recent 1997/98 warm event and its transition to a tropical cool phase. To first order, the shifting of eastern North Pacific storm tracks over N. America during the winter of 1997/98 seemed to be captured at least qualitatively. This mimicking of remote tropical forcing extends even to the transition to a La Nina cool phase. In particular we have seen that increased subsidence over Mexico / Caribbean / Central America sector accords well with observations of droughts there in Spring 1998. After the onset of cold SST anomalies by mid-year, the Fall 1998 over-abundance of precipitation in the equatorial Americas is also captured to a reasonable degree. We are currently examining vertical mean water and energy budgets to understand the thermodynamic linkages during these anomalous periods.

5. Surface water characteristics in NCEP global spectral model and reanalysis

Roads et al. (1999) compared characteristics of the National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) reanalysis surface water budget are compared to the surface water budget characteristics in a long-term simulation with the NCEP global spectral model (GSM) used in the reanalysis. There are many geographic similarities. There are a few differences though, mainly because the reanalysis has a source (artificial) of water from a seasonally varying damping (forcing) term. Because the GSM does not have this (forcing) term, the GSM surface becomes dryer and ultimately has decreased land evaporation and precipitation. Since evaporation variations are strongly related to surface air and skin temperature variations, this decreased GSM surface water is also associated with increased land temperature. However, the GSM surface water variability is greater because the reanalysis time constant (60 days) used to damp (force) the surface water back to the assumed climatology is shorter than characteristic land surface parameterization hydrologic times, which are of the order of 6 months. In agreement with the decreased surface water variability, the reanalysis evaporation variability is also less than the evaporation variability in the GSM. This artificial time constraint may be a reason that the reanalysis temperature predictability by surface water is less than the demonstrated GSM predictability. Characteristics of the US surface water and energy budgets in the NCEP regional spectral model (RSM) and the driving NCEP/NCAR

(NCEPR) reanalysis were subsequently examined by Roads and Chen (2000).

6. Soil Moisture – Atmosphere Thresholds

Oglesby et al. (2001b and 2001c) investigated the potential predictability of the effects of warm season soil moisture anomalies over the central U.S. has been investigated using a series of GCM experiments with the NCAR CCM3/LSM. Three different types of experiments have been made, all starting in either March (representing precursor conditions) or June (conditions at the onset of the warm season): (1) 'anomaly' runs with large, exaggerated initial soil moisture reductions, aimed at evaluating the physical mechanisms by which soil moisture can affect the atmosphere; (2) 'predictability' runs aimed at evaluating whether typical soil moisture initial anomalies (indicative of year-to-year variability) can have a significant effect, and if so, for how long; (3) 'threshold' runs aimed at evaluating if a soil moisture anomaly must be of a specific size (i.e., a threshold crossed) before a significant impact on the atmosphere is seen. The 'anomaly' runs show a large, long-lasting response in soil moisture and also quantities such as surface temperature, sea level pressure, and precipitation; effects persist for at least a year. The 'predictability' runs, on the other hand, show very little impact of the initial soil moisture anomalies on the subsequent evolution of soil moisture and other atmospheric parameters; internal variability is most important, with the initial state of the atmosphere (representing remote effects such as SST anomalies) playing a more secondary role on seasonal and shorter time-scales. The 'threshold' runs, devised to help resolve the dichotomy in 'anomaly' and 'predictability' results, suggest that, at least in CCM3/LSM, the vertical profile of soil moisture is the most important factor, and that deep soil zone anomalies exert a more powerful, long-lasting effect than do anomalies in the near surface soil zone. We therefore suggest that soil moisture feedbacks may be more important in explaining prolonged decadal to century-long droughts evident in the historic and recent prehistoric records, but less important on a seasonal to interannual time-scale.

7. NCEP/NCAR and ECMWF Reanalysis Surface Water and Energy Budgets for the GCIP Region

Surface water and energy budgets from the NCEP/NCAR and ECMWF reanalyses were compared by Roads and Betts (2000) with each other and available observations over the Mississippi River Basin, which is a focus of the Global Energy and Water Cycle Experiment (GEWEX) Continental International Project (GCIP). There are a number of noticeable differences and similarities in the large-scale basin averages. NCEP/NCAR's reanalysis seasonal precipitation and runoff are larger than the available observations; presumably evaporation and surface water variations are also too large. ECMWF reanalysis precipitation is much closer to the observations, whereas the corresponding surface runoff and probably seasonal surface water variations are too small. NCEP/NCAR and ECMWF reanalysis seasonal energy components are more similar to each other. NCEP/NCAR and ECMWF interannual variations are also comparable indicating that these reanalyses can probably be used to begin to study interannual variations. Nonetheless, improved land surface parameterizations are needed to better depict surface water and energy processes, and in particular, variations in seasonal surface water and runoff.

8. Evaluation of the Land Surface Water Budget in NCEP/NCAR and NCEP/DOE AMIP-II Reanalyses using an Off-line Hydrologic Model

The ability of the NCEP/NCAR reanalysis (NRA1) and the follow-up NCEP/DOE AMIP-II reanalysis (NRA2), to reproduce the hydrologic budgets over the Mississippi River basin were evaluated by Mauer et al. (2000, 2001) using a macroscale hydrology model. This diagnosis is aided by a relatively unconstrained global climate simulation using the NCEP global spectral model, and a more highly constrained regional climate simulation using the NCEP regional spectral model, both employing the same land surface parameterization (LSP) as the reanalyses. The hydrology model is the Variable Infiltration Capacity (VIC) model, which is forced by gridded observed precipitation and temperature. It reproduces observed streamflow, and by closure is constrained to balance other terms in the surface water and energy budgets. The VIC simulated surface fluxes therefore provide a benchmark for evaluating the predictions from the reanalyses and the climate models. The comparisons, conducted for the 10-year period 1988-1997, show the well-known overestimation of summer precipitation in the southeastern Mississippi River basin, a consistent overestimation of evapotranspiration, and an underprediction of snow in NRA1. These biases are generally lower in NRA2, though a large overprediction of snow water equivalent exists. NRA1 is subject to errors in the surface water budget due to nudging of modeled soil moisture to an assumed climatology. The nudging and precipitation bias alone do not explain the consistent overprediction of evapotranspiration throughout the basin. Another source of error is the gravitational drainage term in the NCEP LSP, which produces the majority of the model's reported runoff. This may contribute to an overprediction of persistence of surface water anomalies in much of the basin. Residual evapotranspiration inferred from an atmospheric balance of NRA1, which is more directly related to observed atmospheric variables, matches the VIC prediction much more closely than the coupled models. However, the persistence of the residual evapotranspiration is much less than is predicted by the hydrological model or the climate models.

9. CSE Water and Energy Budgets in the NCEP-DOE Reanalysis II

During the past several years, the Global Energy and Water Cycle Experiment (GEWEX) continental-scale experiments (CSEs) have started to develop regional hydroclimatological datasets and Water and Energy Balance (WEBS) studies. To provide some global background for these regional experiments, Roads et al. (2001) described vertically integrated global and regional water and energy budgets from the National Centers for Environmental Prediction – Dept. of Energy (NCEP-DOE) reanalysis II (NCEPRII). As was shown, maintaining the NCEPRII close to observations requires some nudging and this nudging is an important component of analysis budgets. Still, to first order we can discern important hydroclimatological mechanisms in the reanalysis. For example, during summer, atmospheric water vapor, precipitation and evaporation as well as surface and atmospheric radiative heating increase and the dry static energy convergence decreases almost everywhere over the land regions. We can further distinguish differences between hydrologic cycles in midlatitudes and monsoon regions. The monsoon hydrologic cycle shows increased moisture convergence, soil moisture, runoff, but decreased sensible heating with increasing surface temperature. The midlatitude hydrologic cycle, on the other hand, shows decreased moisture convergence and surface water and increased sensible heating.

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